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ABSTRACT

One aim of this study was to identify, in a group of unsuccessful college level problem solvers, the status and use of their declarative knowledge as revealed by students' attempts to solve novel problems in a pencil-and-paper setting. It was hypothesized that for some unsuccessful problem solvers, their problem representation could be improved by structuring the process of problem solving to prevent premature implementation of procedures before the problem had been understood. A second aim of the study was to elucidate the performance of unsuccessful problem solvers attempting novel problems in a computer-based environment that imposed a structure on problem solving and provided feedback during the process of problem solving. It was hypothesized that obligate translation of given data should facilitate the disembedding and elaboration of relevant information from a problem statement, and so enhance a student's problem representation. Difficulties in getting started on a problem were identified as due in part to inappropriate or missing declarative knowledge, and to a failure to access and use this knowledge. The study showed that a computer-based setting can provide information about the declarative knowledge base of unsuccessful problem solvers. (MVL)

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# Problem Solving in a Computer-based Setting with Verbal to Visual Recoding of Given Data

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**Problem Solving in a Computer-based Setting with Verbal to Visual Recoding of Given Data**

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## Introduction

Problem solving encompasses a range of skills central to the domain of genetics. A key role of teachers is to facilitate the development in their students of these skills to an operational level that equips them to solve genetics problems, not only ones that directly mirror problems used in the process of skill acquisition, but also problems that represent variants not previously encountered. These skills are introduced to, and are developed and refined by students during their exposure to appropriate learning experiences in genetics.

Successful problem solving requires both relevant declarative and procedural knowledge, and an interaction between the two that results in the construction by students of procedural sequences matched to and suitable for the problem in hand.

The acquisition of procedural sequences or 'productions' differs from that for declarative knowledge, in that the former are acquired more gradually, inductively, and only in response to practice. Anderson (1983) proposes that practice and performance during procedural learning can eventually lead to

- the creation of task-specific productions that can be applied automatically (the process of 'proceduralization');
- the collapse of frequently-repeated sequences into single productions (the process of 'composition');
- the 'tuning' of productions as they are applied to problem-solving.

When the features of a problem task are recognized as matching the conditions of a previously-acquired production, that production is applied in solving the problem. Accurate recognition of the salient features of a problem depends on an appropriate declarative knowledge base. Anderson's model provides a rationale for giving students time to explore and construct appropriate sequences of procedures for solving problems. These learning experiences should include qualitatively different problem settings, so that problems of many different types can be encountered, and productions can gradually be learned.

In the following section, a brief overview of problem types is provided as a background to the study reported in this paper.

### Types of problems

In scrutinizing problem solving in genetics, as in any domain, the problem-solving task itself is an important variable. Problem-solving tasks may be categorized in various ways (for example, Simon's (1978) well-structured or ill-structured problems). Some classifications are based on factors intrinsic to a problem, and some are based on extrinsic factors, an important one being the knowledge brought to the task by the problem solver.

Problem-solving tasks can vary in the **degree of familiarity**, and may range from *familiar* to *novel*. This classification is based on an extrinsic factor, namely a student's recognition of the problem. A familiar problem is one that is accurately recognized by a student as corresponding to a type that has previously been met under circumstances in which the student has over time been able to develop, practice, and refine procedural sequences into a production appropriate for solution of this type of problem. In these cases, the features of a problem must be recognized, extracted, and matched to the conditions of an established production which is then used in obtaining the solution. Recognition of the features of a problem calls on the solver's declarative knowledge.

In cases where the relevant features of a problem are rapidly extracted and identified as matching an appropriate production, the problem is 'very familiar', the solver will appear to know the route required for solution as soon as the problem is read, and 'time on task' is principally spent in applying procedures required for solution rather than in searching for an appropriate procedure. The work of several investigators, including Fredericksen (1982) supports the view that reading can go hand-in-hand with other cognitive processing, so that solution strategies may be identified as a problem is read. Where this 'auto-pilot' type of approach to problem solving occurs, the problem in question for that solver in that context is an 'exercise' rather than a 'problem' in the sense of Bodner and McMillan (1986), who identify as problems, those situations in which the route to solution is not known to a solver, and identify as exercises, those situations is which the route is known. Problem solving characterised by an 'auto pilot' approach that is based on a depth of understanding of and a breadth of operations in genetics and involves proceduralization of sequences is typical of experts in a domain. This approach must be distinguished from the inflexible use of rotely-learned algorithms in problem solving, an approach has been inferred to occur with some students of genetics. While this approach may result in correct answers to problems provided they conform to a particular pattern, it may not reflect meaningful understanding of the relevant concepts (Stewart and Dale 1981).

A problem identified as novel for a particular student is one that is unfamiliar to and unrecognised for the solver. This situation may arise in several ways. For example, a student:

- may not have acquired a production appropriate for solution because s/he has not previously been exposed to a problem of that type;
- may be unable to execute an existing production because of a failure to identify and extract the relevant features of the problem for matching to the conditions of a production.

Where the problem corresponds to one that has never been encountered by a student, the problem is novel in the truest sense. For novel problems, 'time on task' involves a major proportion of time spent in disembedding relevant information from the problem statement and in selecting and trialling different procedures, in addition to time spent in applying the procedures finally identified as appropriate for solution. Solutions to novel problems can be reached through a slow process that involves interpretative application of declarative knowledge (Anderson loc. cit.). Hence where students' declarative knowledge is deficient, their problem solving will be poor.

Where a student has acquired a production, but fails to identify the relevant features of a problem so that no match can be made to the conditions of a production, the problem may be regarded as 'pseudo-novel'. Failure to identify relevant features of a problem may be attributed to several causes, in some cases reflecting defects in the student's declarative knowledge base, and in other cases, reflecting defects in procedural knowledge.

For example, failure by a student to identify problem features may reflect:

- inadequate declarative knowledge, such as missing or inaccurate concepts or missing or inaccurate relationships between concepts;
- sparsely elaborated concepts, which while accurate, are poorly linked to related concepts;
- restricted accessibility to knowledge held by the student; where knowledge relevant to the problem is held, but not accessed where relevant, it may be termed 'inert' knowledge (Whitehead (1929) cited in Bransford *et al.* (1986));
- inappropriate approach to the task, such as the trialling of possible solutions without adequate consideration of the problem task, even when relevant declarative knowledge is adequate.

In the case of problems whose novelty for a particular student is due to any of these factors, the student will be unable to match the conditions of a production required for solution of a particular problem, and may proceed to a solution slowly, if at all, by identifying procedures in turn and seeing if they can be applied to the problem. Problem solution involving a novel problem in a structured situation may assist students in elaborating an existing concept or restructuring an inaccurate concept, in forging links between two related but previously isolated concepts, in recognizing previously-ignored

data as relevant, or in making a systematic consideration of the problem task rather than trying to remember solutions.

In terms of intrinsic factors, many classifications of problems are possible, including the major type of reasoning required, degree of disclosure, degree of explication, contextual reference, degree of complexity, and source of data. Some classifications represent the end points of a continuum along which a given problem may be located; other classifications are dichotomous, so that a given problem may be classified as conforming to one or other of two possible classifications. Summaries of some classifications taken from Kinnear (1989) follow:

Problems can vary in the **type of reasoning** that is principally required for their solution. Problems can have a major requirement for *deductive* reasoning or for *inductive* reasoning depending on the nature of the data supplied and the question asked. In problems requiring a major component of deductive reasoning, the problem statement specifies a genetic system and identifies the parental genotypes; the required output is a prediction of the expected offspring from a nominated cross. In problems with a major requirement for inductive reasoning, the problem statement provides data about the results of a cross, from which students are required to generate an explanatory model consistent with these data.

Problems can vary in their **degree of disclosure**, depending on whether the problem statement provides complete or incomplete information. In the case of *full* disclosure, all relevant elements are identified and specified. In the case of *partial* disclosure, however, some elements are left unspecified, and students must make assumptions and qualify their answers. For example, the statement below leaves some relevant elements of the genetic system unspecified, including whether or not the genes are linked or not, or whether or not the genes interact in their phenotypic expressions:

> *Two organisms, each genotype **Aa Bb**, were crossed to produce a large number of offspring. What phenotypic ratios would be expected among the offspring?*

In this case, an answer, such as 'Four classes of offspring approximating a ratio of 9:3:3:1 would be expected', should strictly be qualified by a rider that would include 'Assuming that the genes are not linked . . . '.

Problems can vary with regard to the **degree of explication** of the data in the problem statement. Data may be *fully* or *partially explicated*. In the latter case, some information related to the problem is implicit and must be inferred. A student's ability to make these inferences depends on the quality and interrelatedness of his/her declarative knowledge. For example, while the statement below provides full disclosure of a genetic system, the data are not fully explicated:

> *A green, two-toed female, genotype **Gg Tt** was crossed with a purple , four-toed male, genotype **gg tt** . . . . .*

On the basis of knowledge of genetics, including the conventions for allelic notation, several valid inferences may be made, including:

- color and toe number are controlled by separate genes;
- each gene has at least two alleles;
- neither gene is sex-linked;
- green color phenotype is dominant to purple;
- four-toed phenotype is recessive to the two-toed phenotype;
- the organism concerned is diploid.

Problems can vary in their **contextual reference** and may be expressed in either *local* or *global* terms. A problem expressed in local terms might include statements such as:

> *Two tailless (Manx) cats produce a litter of kittens all of which have tails. A second litter from the same parents includes some kittens with tails and some Manx kittens. Describe a genetic system consistent with this observation.*

A problem expressed in global terms might include statement such as:

> *Two parents display different phenotypes. Their offspring are of two kind, with all male offspring showing the maternal phenotype and all female*

*offspring showing the paternal phenotype. Outline the features of a genetic system that can explain these observations.*

Problems can vary in their **degree of complexity**. Complexity is a function both of the number of variables operating in a genetic system and of the values assigned to those variables. An example of a genetic system of *low* complexity is one involving a single gene having two alleles, with one allele being dominant to the other in its phenotypic effects. An example of a genetic system of *high* complexity is one in which two genes are assorting, with one gene being X-linked and having two alleles that are incompletely dominant in their phenotypic effects, and with the second gene being located on an autosome and having three alleles that show decreasing dominance in their phenotypic effects.

Problems can vary in terms of the **source of the data**. Data may be *given* in the problem statement or may be *generated* by the problem solver. Where data are given, they consist, for example, of verbal descriptions of offspring from a cross. In this case, the data set is *static* and *closed*. Where data are generated by the problem solver, this capability is provided through interactive use of the program. In this case the data set is *dynamic* and *open*, and may be added to by problem solvers as they choose.

## Stages of problem solving

Problem solving has been identified by many investigators as comprising several stages organized into a more or less consistent sequence. While problem solving is not a series of discrete and delimited stages, these stages provide a guide that can assist analysis of the complex process of problem solving.

Among the many problem-solving stages identified are Polya's (1945) Production, Incubation, and Illumination; Newell and Simon's (1972) Input Translation, Internal Representation, Method Selection, Implementation and Monitoring, Reformulation; Hayes's (1981) Finding Problem, Representing Problem, Planning Solution, Carrying Out Plan, Evaluating Solution, and Consolidating Gains; Brandsford and Stein's (1984) Identify, Define, Explore, Act, Look and Learn. Essentially all schemes include early in problem solving, a process often termed problem representation. These early stages correspond to the period of 'getting started on a problem' during which the solver is faced with the task of deciding which of many possible directions should be followed.

According to Chi et al. (1981), problem representation is an outcome of an initial categorization of the problem, and is a cognitive structure relating to the problem, constructed by the solver on the basis of his/her domain-related knowledge and its organization. Hence the quality of students' problem representations influences their facility in problem solving. Hayes (1981) describes problem representation as a process of forming an internal representation of the problem that includes the initial state, the goal, operators and their restrictions. The construction of an internal representation of the problem by the solver is an active process involving interpretation, and the addition and subtraction of knowledge, leading to a transformation of the problem. Bodner and McMillen (1986) identify the early stage of problem solving as a 'holistic' stage during which relevant information is disembedded from the problem, elements are manipulated, and the problem statement is elaborated, so that the problem is restructured, and the initial and goal states recognised.

Problem representations are not accessible to direct study, and information about them may only be inferred from observed problem-solving behaviors. However, the quality of problem representation would be expected to reflect in part the quality, accessibility, and use of a student's declarative knowledge. Where the problem representation is inferred to be poor, this would be expected to lead to difficulty in problem solving. It does not follow, however, that a high quality problem representation will lead to ease of problem solving, since appropriate use of procedural knowledge is also required as a working complement to declarative knowledge for the identification and implementation of a selected strategy. Many examples of errors in the use of procedural knowledge have been identified in problem solving in a genetic context (for example, Simmons (1988), Hackling and Lawrence 1988, Smith 1988), and these can act as significant barriers to successful problem solving.

Computer-based problem solving

Computer use may be integrated into problem-solving activities in genetics. For example, coupled with appropriate software, computers can provide genetics students with problems of a type in which a problem statement, but no data, are given. In enabling students to generate data, this mode of computer use extends the repertoire of behaviors that can be studied during problem solving. Problems of this type elevate to an essential component of the problem-solving process, the dual requirements to generate data and to make decisions regarding their sufficiency and relevance, and consequently provide a convenient window onto this aspect of students' operations during problem solving (Kinnear 1986).

Other modes of computer use are possible. For example, computers may be used to enable students to specify the components of a genetic system, set up crosses, and observe outcomes. It may be argued that a student could carry out an equivalent task in a pencil-and-paper mode, and that computer use is redundant adding nothing to the task. It is asserted, however, that this mode of computer use can significantly change a problem-solving environment through the provision of consequential feedback throughout the process. For example, consider the problem:

> *In dogs, one gene controls color and has the alleles, black and brown, with black (**B** ) being dominant to brown (**b** ). A second gene controls white spotting, and has the alleles solid (unspotted) and spotted, with solid (**S** ) being dominant to spotted (**s** ). The genes show independent assortment. What different kinds of offspring could be produced by a cross of two parents each genotype **Bb Ss** ?*

As a pencil-and-paper task, the solution of this problem might be pursued by the setting up a Punnett square for the cross of two parents heterozygous for two independently assorting autosomal genes. In reaching a solution, a solver may be oblivious of the implied chromosomal locations of the genes and of the consequences for gene behavior. In a pencil-and paper task, feedback to the solver is commonly given in the form of a summative statement such as: 'The correct answers is . . .', or as a summative assessment of the student's solution such as: 'Your answer is (in)correct because . . . .'

The solution of this same problem as a computer-based task, however, may engender different demands, as for example, by requiring the solver to specify explicitly the genetic system, including the chromosomal locations of the genes. The requirement to explicate these details creates a different problem environment from a pencil-and-paper task. Feedback in the case of a computer-based task is consequential, with the solver seeing the results of each decison in verbal or in visual form. Further, a computer-based environment allows for an immediate check by students of their answers, simply by carrying out the simulated cross and seeing if their predictions are consistent with the results.

A computer-based environment of this type imposes a structure on and organizes the solver's processing. For example, in a computer-based environment:

- a student's cognitive processing may be forced into a serial mode because the computer organizes the student to address one goal at a time;
- a student is obliged to attend to all goals on the path to the solution in a pre-determined order, and does not have the option to ignore or bypass a goal;
- a student is required to make explicit decisions about inclusion or exclusion of factors (for example, lethality) which, if not relevant, are not simply omitted and implicitly identified as 'to be excluded';
- a student's choice of value for a variable is constrained within a valid range such that, even if a student chooses an incorrect value, s/he is buffered from selecting an illogical value.

For the computer-based task, students proceed along a route that is determined by the computer, but with the input at each point being student-controlled. This route does not necessarily lead to a correct solution, since inappropriate responses at decision points along the way can put the student off-track.

These considerations relating to a computer-based setting combine to extend the time required to solve a problem, to organize the process, and to limit possible errors. For students who have mastered a particular type of problem, this enforced prolongation of the problem-solving process comprises an unnecessary delay, and the organization and error limitation are unnecessary constraints on the student; such students can find the computer-based setting frustratingly slow. However, for students who have a consistently poor record in solving genetics problems, the structure imposed by a computer-based environment may force consideration of relevant factors that might otherwise be overlooked, may assist in clarifying concepts, may facilitate recognition of relationships between concepts, may aid in the recognition of critical information, and may assist identification of the point at which the process of solving a particular problem falters. The computer-based environment may assist students in constructing a problem representation that is different from that produced in a pencil-and-paper setting, and so give students new perspectives on a problem.

Aims of study

One aim of this study was to identify, in a group of unsuccessful problem solvers, the status and use of their declarative knowledge as revealed by students' attempts to solve novel problems in a pencil-and-paper setting. It was expected that, for some unsuccessful problem solvers, difficulty in solving novel problems reflected an internal problem representation of poor quality that was due to a premature implementation of procedures before a problem had been understood, or to defects in the solver's declarative knowledge or to failure to use declarative knowledge.

It was hypothesized that for some unsuccessful problem solvers, their problem representation could be improved by structuring the process of problem solving to prevent premature implementation of procedures before the problem had been understood. A second aim of the study was to elucidate the performance of unsuccessful problem solvers attempting novel problems in a computer-based environment that imposed a structure on problem solving and provided feedback during the process of problem solving.

It was hypothesized that obligate translation of given data should facilitating the disembedding and elaboration of relevant information from a problem statement, and so enhance a student's problem representation. Valid translation draws on declarative knowledge and requires an understanding of the relevant concepts and of relationships between concepts. The study sought to examine the effect of one feature of a computer-based setting, namely the provision for translation and expansion of data given in the problem, including its recoding from verbal to visual form.

**Materials and Methods**

Subjects

The subjects of this study were a group of College students (N = 8) who had previously completed an introductory unit on basic transmission genetics. This small group was selected from a larger group and comprised students who had a low record of success for problem solving in transmission genetics, other than for problems with a low level of complexity. The selection was based on students' past performances, and was confirmed by their performance on two pencil-and-paper problems, as described below.

The problems

The problem-solving tasks used in this study had a major requirement for deductive reasoning, requiring students to argue from cause to effect. The problems provided full disclosure, the data were given, rather than student-generated, but were not all fully explicated, so that students were required to make valid inferences to expand some of the data. The problems were designed to be of a sufficiently high level of genetic complexity that students would not be expected to proceed automatically to their solution. The

problems were also intended to test students' conceptual understanding as demonstrated by their operational recognition of genetic terminology.

The path to solution of these problems involved translation and expansion of some data given in the problem statement in a general form (e.g., X-linked gene) into a more specific, but congruent form (e.g., putting a gene locus on the X-chromosome).

P1 In a species of mammal, body color is controlled by an X-linked gene with the alleles *green* and *purple* ; these alleles show partial (incomplete) dominance in their phenotypic effects. An autosomal gene controls tail angle, and has the alleles *curly* and *straight* , with curly being dominant to straight.
A bi-colored (green and purple) organism with a curly tail was crossed with a purple organism with a straight tail.

i. Could a purple female offspring with a straight tail be produced from a cross of these types of parents?
ii. Could a green female offspring with a curly tail be produced by these parents?
iii Draw a diagram showing possible chromosomal locations of the alleles in each parent.

C1 Isomorphic with problem P1, but with genes and alleles replaced:
In a species of mammal, bar width is controlled by an X-linked gene with the alleles *wide* and *narrow;* these alleles show partial dominance in their phenotypic effects. An autosomal gene controls ear shape, and has the alleles *square* and *diamond*, with square being dominant to diamond.
A organism with standard bar width (in between narrow and wide) and square ears was crossed with an organism with narrow bars and diamond ears.

i. Could a female offspring with *narrow* bars and *diamond* ears be produced from a cross of parents of these types?
ii. Could a female offspring with *wide* bars and *square* ears produced by these parents?
[iii Draw a diagram showing possible chromosomal locations of the alleles in each parent.]

P2 In an animal species, an autosomal gene controls toe number, with *2-toed* being recessive to the *4-toed* condition. Another autosomal gene, assorting independently of the toe number gene, controls leg length and has three alleles, *lanky, medium,* and *dwarf* that show complete dominance. The order of dominance is lanky is dominant to both medium and dwarf, and medium is dominant to dwarf.

i. How many different kinds of offspring could be produced from the following cross:
a female, heterozygous for 4-toed and lanky leg length, known to be carrying the allele for medium leg length, with a male with 2-toes and dwarf leg length?
ii. Would any of these offspring show the same phenotype as the father, that is, 2-toed dwarf?
iii Draw a diagram showing possible chromosomal locations of the alleles in each parent.

C2 Isomorphic with P2 but with genes and alleles replaced:
In an animal species, an autosomal gene controls chin shape, with *indented* being recessive to the *pointed* condition. Another autosomal gene, assorting independently of the toe number gene, controls fin angle and has three alleles, *vertical, oblique,* and *flat* that show complete dominance. The order of dominance is vertical is dominant to both oblique and flat, and oblique is dominant to flat.

i. How many different kinds of offspring could be produced from the following cross:

a female, heterozygous pointed chin and vertical fins, known to be carrying the allele for oblique fin angle, with a male with indented chin and flat fins?

ii. Would any of these offspring show the same phenotype as the father, that is, indented chin and flat fins?

[iii Draw a diagram showing possible chromosomal locations of the alleles in each parent.]

Each subject attempted all four problems, and from each pair, one problem was done as a pencil-and-paper task (P1 and P2), and its isomorph was later done as a computer-based task (C1 and C2).

Pencil-and-paper task

Students were requested to read and answer the problems (P1 and P2). Pencils and paper were made available and students were asked to record their working. No time limit was set so that students were not under pressure to hurry through the task, and were free to proceed using strategies of their choice. Students' working of each problem was analysed to identify inferences made, and knowledge applied in attempting to solve these problems. Performance on these problems confirmed the selection of the group of eight unsuccessful problem solvers who were the subjects of further investigation.

Computer-based task

During a later session, the unsuccessful solvers (n=8) attempted two problems (C1 and C2) in a computer-based setting. For the computer-based problem, students were requested to think aloud, and their comments were audiotaped and transcribed. The problems were isomorphs of those previously attempted in the pencil-and-paper setting, and their solution was undertaken in a computer-based setting in which the subjects used a computer program (Kinnear 1989) to specify, within limits, several variables determining a genetic system (number of pairs of autosomes, sex chromosome system, number of genes, number of alleles per gene, relationship between alleles, gene function, chromosomal location of genes, presence of lethality). Students recorded their choices on record sheets. This program also allowed students to specify parental genotypes and to obtain offspring from the nominated parents. Students' decisions at each point were recorded and inferences made, and knowledge applied were identified.

Students were requested to indicate their answers before using the program to obtain offspring from the parents. After obtaining offspring, students could, on the bais of this information, make their own assessment of the validity of solutions reached. Part (iii) of problems C1 and C2 was attempted after the students had terminated use of the computer program.

Post testing

The subjects were tested with pencil-and-paper problems of comparable genetic complexity one week after the completion of the computer-based tasks.

**Results and Discussion**

Because data given in the problems were not fully explicated, students were required as part of the problem-solving process to make inferences to expand these data. Figure 1 lists the data given in the problems and identifies valid inferences relevant to the solution of the problems.

Pencil-and-paper tasks

The unsuccessful group was identified on the basis of either an incorrect answer to or a failure to solve the two pencil-and-paper problems (P1 and P2). In many cases, the students' paperwork revealed errors that may be assumed to have arisen from missing or poorly elaborated declarative knowledge, or from a failure to access knowledge relevant to the specific problem task.

An analysis of the performance of unsuccessful solvers on problem P1 is shown in Figure 2. Only two subjects (S1 and S2) apparently identified the cues 'mammal' and 'X-linked gene' in the problem statement and recognized that a female has two alleles of this gene and a male has only one allele. These two subjects, however, could not translate phenotypes into correct genotypes. Subject S5 identified the presence of the XX/XY sex chromosomes, but assigned an allele to each of the X chromosome and the Y chromosome of the male. It is not possible to conclude whether the other five subjects simply missed these cues, or whether they noted them but failed to realise their relevance to the problem. Three of these five students (S3, S4, and S6) assigned a genotype to the female parent which, while 'correct' in isolation and in terms of the number of alleles, was not based on an understanding or a recognition of the operational consequences of X-linkage. This lack of understanding of, or failure to recognize, X-linkage was indicated by the fact that none of these subjects assigned a hemizygous genotype for the male.

All subjects recognized that the bicolored parent was heterozygous and assigned an appropriate genotype. Five of the eight students correctly identified the straight tail condition as homozygous recessive. Although the group was deliberately selected as being unsuccessful on solving genetics problem, it is interesting to note how early the breakdown of the process occurred: none of the eight students assigned correct genotypes for both parents, and only one student identified gametes consistent with the genotypes assigned to the parents.

Figure 3 show an analysis of the performance of unsuccessful solvers on problem P2. One finding was that, as expressed in the parental genotypes assigned, one student only (S8) successfully handled the three-allele system. Subject S2 wrote parental genotypes incorrectly in terms of three gene loci rather than two (assigned genotype: ***Tt Ll Ss***), and subject S4 wrote genotypes that made the parents diploid for the toe number gene, but triploid for the leg length gene (assigned genotype ***Tt Lll***).

Whether the 'knowledge errors' exhibited by students are due to incorrect declarative knowledge or to failure to access and use knowledge cannot be decided from these results. Some clarification was possible through the identification of errors restricted to one setting, since errors made in the pencil-and-paper setting, but not in the more-structured computer-based setting, are more likely to be errors due to failure to access and use declarative knowledge rather than to defective declarative knowledge. Where comparable errors occur in both the computer-based and the pencil-and-paper setting, it is not possible to distinguish between these causes.

Where students were asked to draw a diagram showing possible chromosomal locations of the alleles, only three students attempted this, with five making no attempt at this task for either of problems P1 or P2. The three subjects who attempted this task all made errors; for example, subject S4, working on problem P2, drew two alleles of the same gene at different locations on the same chromosome; subject S2 working on problem P2 indicated the locations of different alleles of the same gene as being on non-homologous chromosomes; subject S1, working on problem P2, correctly translated a parental genotype to appropriate positions on chromosomes, but the chromosomes were incorrectly represented with members of one homologous pair of autosomes differing significantly in length.

The difficulty in recognizing and describing the relationship between genes and chromosomes that was seen in this study is in accord with findings of other investigators who report a consistent error in genetics students stemming from their failure to grasp the relationship between genes, alleles, and chromosomes (for example, Stewart1982, Tolman1982). It appears that subjects who identified and wrote parental genotypes (correct or incorrect) on their worksheets were apparently unable to represent a link of any kind between the allele symbols they wrote and chromosomes. Knowledge,

represented as abstract propositions and spatial images, encompassing relationships between genes, alleles, and chromosomes is apparently missing or poorly developed in, or not accessed by this group of subjects. In the presumed absence of or access to this knowledge, it is expected that students will fail to recognize and interpret behaviors of genes and alleles (such as segregation of alleles, independent assortment of genes, and distortion of expected segregation ratios in the case of linked genes) as consequences of chromosomal events during meiosis (such as disjoining of members of homologous pairs of chromosomes, independent behaviour of non-homologous chromosomes, and crossing-over between homologous chromosomes).

Overall, this group of unsuccessful problem solvers in the pencil-and-paper setting showed poor ability to make valid inferences from the data given in the problems, and appeared to tackle the problems with little, if any, prior planning. This suggests that little time was occupied in the early stages of problem solving during which the problem is identified and an internal representation is formed. The strategy used by students appeared to be predominantly one of trying to remember a solution, rather than one of systematic analysis and productive manipulation of knowledge. This grasping for a successful procedure appears to come at the cost of ignoring the problem-specific declarative knowledge. This finding is consistent with that of other investigators, for example, Smith (1988), who have found that unsuccessful problem solvers show a range of inappropriate behaviors that reflect evidence of little planning, including making careless errors, paying less attention to detail in the problem, and attempting one-step solutions.

Computer-based tasks

Figure 4 shows the critical decisions and available choices for problems C1 and C2. The sequence of decisions shown corresponds to their order in the program. Subjects' performance on problems in the computer-based setting was superior to that in the pencil-and-paper setting both in terms of completion of sub-goals and in terms of arriving at an answer. Five of the 8 students reached a correct solution for problem C1 and four of the group reached a correct solution to problem C2. Figure 5 summarizes the results for the student group for problem C1 and C2.

The transcripts revealed that students generally spent some time considering each decision in the computer based setting and referred back to the problem statement. Overall, students made an appropriate selection from the available options. The decision points that required some time before a response was initiated were in response to the prompt relating to the number of autosomes, and to the prompts: 'Do you want to have lethality? (Y/N)'. The decision that required the most time to be implemented, and presumably the greatest cognitive processing, was to give each gene a chromosomal location. This was in response to the prompt: 'Use ARROWS to locate the gene then press RETURN when done'. As students moved an arrow across the on-screen images of chromosomes to successive positions, their verbalizations were interrupted by long periods of silence. This decision making involved a recoding by students of a verbal cue given in the problem statements such as 'X-linked gene' or 'an autosomal gene', or 'a second gene that assorts independently of the first gene', and its translation into a visual representation that captured the operational consequences of the cue as appropriate physical location(s) of the gene(s). All students identified correct locations for the two genes in problem C1 which related to an X-linked gene and an autosomal gene. This finding suggests that errors observed in problem P1 relating to this were due to failure to access and use relevant declarative knowledge rather than to incorrect knowledge. For problem C2, however, which related to an autosomal gene and a second gene *assorting independently* of the first, the location chosen for the second gene by four of the students was on the same chromosome as the first gene; for the other students, the second gene was located on a non-homologous chromosome. However, the transcripts of two of these students suggests that these correct locations were chance choices. The term 'independent assortment' appeared to be poorly recognised by this student group, and this lack of recognition appeared to be based on a lack of relevant declarative knowledge. These findings indicate that verbal to visual recoding of this nature can assist in distinguishing whether a student's difficulty with problem identification and representation is due to defective declarative knowledge or to failure to access knowledge.

The audiotape revealed that all students reacted with initial surprise when they were given the menu of choices for the male parent's genotype for the X-linked bar width gene in problem C1. Only two choices were available, namely hemizygous for narrow bars or hemizygous for wide bars, whereas three choices were available for the female parent's genotype, namely homozygous narrow, homozygous wide, or heterozygous medium.

The decision points at which most errors occurred was in handling the chromosomal location of the genes and the operation of a three-allele system in the case of problem C2, and in assigning parental genotypes in both problems C1 and C2. Specific errors made by students in problem C1 included the incorrect assignment of the female parent as homozygous for square instead of heterozygous, and the failure to identify the female parent as the obligate standard-barred organism, so making it impossible to assign an appropriate hemizygous genotype for the male parent that cannot be heterozygous medium-barred. In the case of problem C2, the common error in chromosomal location was to locate independently assorting genes on the same chromosome. Of the five students correctly assigning both parental genotypes in problem C2, only one was unable to predict that four different kinds of offspring were possible.

A selection of students' comments taken from the audiotapes and relating to the organized specification of the genetic system follows:

(i) *With regard to choosing a sex chromosome system :*
'This doesn't matter. . . does it? I can choose anything I think. . . No. . No. . It has to be. . . has to be XX and . . XX and XY because it's X-linked.' (S4 on problem C1)
'I'll just choose the one I know. . the mammal one. . . . [CHROMOSOMES APPEAR] Yes, that's OK. . . . Uh. . its got to be that, its got to be a mammal. ' (S6 on problem C1)
'Just a minute, hold it. . . . what does it say? . . In a species of mammal. . . Alright, choose a mammal XX XY.' (S3 on problem C1).

(ii) *With regard to deciding on the location the genes :*
'Where does it go? . . . . . Let's try . . . . . can we get it over to the X? . . . Yes here it goes. . . . uh . . keep going . . . OK put it there.' (S7 assigning first gene in C1)
'Now choose the location. . . It's not . . uh . . the X. . . . I'll just leave it here . . . on one.' (S1 assigning second gene in problem C1)
'Now where will I put it . . . . . not sure . . uh . . . . yes it will . . . will have to go . . go on the X.' (S5 assigning first gene in problem C1)
'It doesn't matter where this goes . . . not X. . . but it can't be on the X.' (S1 on assigning second gene in problem C2)
'The first's on one . . so I'll . . uh. .put this one on two. . . why not.' (S2 on assigning second gene in problem C2)

(iv) *With regard to the inclusion or exclusion of lethality :*
'Oh. . what's this? . . . . no. . . let's . . uh . leave it out. . . that will just complicate things.'(S2 on problem C1)
"I don't know . . . want to have lethality . . . no don't want that.'

(v) *With regard to choosing parental genotypes :*
'This looks funny . . . this'll do . . he's got to be . . . be narrow.' (S7 on assigning genotype of male parent in problem C1)
'But where's medium. . there's no medium . . he's medium but the . . uh. . genes aren't there . . the program's wrong.' (S8 on assigning genotype of male parent in problem C1)

The improved performance overall on both problems C1 and C2 is not surprising given that the computer-based setting provided an organization for the subjects' operations, by breaking down a complex task into manageable steps that required students to address sub-goals in turn. The computer-based setting may have assisted students to recognise relevant factors, such as X-linkage, that may otherwise have be overlooked, and so confront explicitly assumptions that may have remained implicit and unrecognised. The computer-based setting also placed restrictions on student choices, so that while students could make an incorrect choice at a decision point (for example, choosing a homozygous genotype instead of a heterozygous genotype), they could not make an

invalid choice (for example, choosing a heterozygous genotype for a male mammal with regard to an X-linked gene). Aspects of the improved performance in the computer-based setting may have been due simply to the constraints placed on possible errors, as for example, when students choose parental genotypes in the computer-based setting they do so from a displayed list, whereas in the pencil-and-paper setting, students must generate genotypes without the assistance of a list from which to make a selection. However, the results of this study support the contention that, in addition, the computer-based setting assisted some students in some aspects of problem solving by providing an organizing structure that helped them retrieve, use, elaborate, and link relevant elements of their declarative knowledge, and that may be presumed to have resulted in more cognitive processing by students directed to the early stages of problem solving, namely problem identification and problem representation. This is consistent with conclusions reached by investigators that in order to facilitate realization of the potential cognitive gains from computer-based explorations, students should be provided with a structure to guide and direct their explorations (Kinnear 1985, Rivers and Vockell 1987, Woodward, Carnine, and Gersten 1988). This improvement was most visible in terms of an elaborated relationship between genes and chromosomes.

The presumed increased processing that is assumed to have occurred in the computer-based setting may result from the action or interaction of several factors. These factors may include

- The longer period of time necessarily spent in the computer-based setting, relative to that in the pencil-and-paper setting, on specifying the underlying genetic system prior to nominating parental genotypes.
- The provision of an organizing structure to assist the students in moving systematically through the knowledge components of the problem.

Comments taken from the transcripts indicate that the orderly specification of the key elements of the genetic system appeared to assist students in recognising relevant variables, and in clarifying relationships between elements in the problem.

- The requirement to translate data given in verbal form in the problem statement into specific operational values.

In the computer-based environment, this translation is obligate, with the program requiring students to make specific decisions that make overt the students' interpretations of and inferences from the data. In a pencil-and-paper setting, this translation may be overt, as when a student draws a diagram or makes an annotation, but it is often covert, or does not occur as when a student simply disregards some data.

- The provision of feedback, often as visual representations, consequent to decisions made by students in response to verbal prompts during the course of problem solving.

Decisions elicit consequential feedback in the form of on-screen verbal or visual representations. Student are placed in a setting where, if in response to the question: How many pairs of autosomes?, they answer "Two", a visual representation of two pairs of autosomes appears on screen. The chromosomal location of a gene is effected by the student moving an arrow across an image of the chromosomes to a selected spot which become the gene locus. This visual feedback can provide students with a clarifying perspective by assisting them to link verbal labels with visual representations of the referent concepts. The use of dual representations, verbal and visual, can potentially enhance processing by aiding encoding, storage, and retrieval of concepts.

The students' attempts at drawing the chromosomal arrangements of the alleles after they had terminated the program were more successful than the attempts associated with problem P1 and P2. The improved performance in the computer-based setting is to be expected since in their interaction with the program, students manipulated visual images, and received feedback in the form of visual images that could provide a model for their own drawings. Images have been shown to assist tasks of recall and recognition (Pavio 1971). Schwartz and Kulhavy (1988) in a study of encoding tactics for remembering maps found spatially-based encoding to be an efficient strategy for preserving memory of spatial relations of a map as a whole. Similarly, it is to be expected that encoding of allelic arrangements on chromosomes will be facilitated by use of images which capture the spatial configuration. The role of pictures and imagery on learning, as distincy from recall, is not clear. In a discussion of the possible role of

pictures in learning, Reid (1984) suggests that, if pictures aid understanding, it is the interaction between pictures and the words they are associated with that is likely to facilitate understanding. Computer-based settings that combine both verbal labels and visual images may contribute to the elucidation of Reid's tentative conclusion.

The post testing of students on comparable pencil-and-paper problems showed that some improvement in performance was maintained over the short term. In particular, it was noted that students spent more time analysing problems, underling key phrases and making simple diagrams, than had been spent in their earlier sessions with pencil-and-paper problems. An important question remains as to whether or not this improvement can be maintained over a longer time course.

**Conclusions and Implications**

This investigation provided some insight into the role of declarative knowledge on problem solving in genetics. The findings reported here refer to one small group of unsuccessful problem solvers on one type of novel problem-solving task. Studies currently in progress will identify the reproducibility and transferability of some the conclusions from this study.

Difficulties in 'getting started' on a problem were identified as due in part both to inappropriate or missing declarative knowledge, and to a failure to access and use this knowledge. These defects in declarative knowledge are assumed to lead to poor quality internal problem representation, so contributing to student difficulties in problem solving. Because declarative and procedural knowledge interact in problem solving, defects in the quality of or access to procedural knowledge act as a barrier to the development of competence in problem solving by inhibiting the flexible and interpretive use of knowledge in novel problem settings and so preventing the construction by students of 'productions' appropriate for solution. This study showed that computer-based setting can provide information about the declarative knowledge base of unsuccessful problem solvers.

Exposure to problem solving in a particular computer-based setting was found to lead to some improvement in problem solving in a group of unsuccessful solvers. One factor in this improvement appears to be the structure imposed on students by this setting, which prevented them from trying solutions before they had developed some understanding of the problem, and acted by requiring students to address sub-goals that assisted their access to and use of declarative knowledge. The obligate recoding of given verbal cues to visual representations may also contribute to problem identification and representation, and at least, can contribute to identifying the nature of errors relating to declarative knowledge.

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| GIVEN IN PROBLEM (P1) | | INFERENCE |
|---|---|---|
| "mammal" & | Inf1 | XX/XY sex chromosome system |
| "X-linked gene" | Inf2 | male will be hemizygous for the X-linked gene and females will have 2 alleles |
| "incompletely dominant" & | Inf3 | bicolor must be heterozygous |
| "X-linked gene" | Inf4 | bicolor organism must be female |
| "autosomal gene" | Inf5 | gene not on a sex chromosome, |
| | Inf6 | gene will assort independently of X-linked gene |
| | Inf7 | each sex has two alleles of the gene |
| "curly being dominant to straight" | Inf8 | curly tail may be homozygous or heterozygous |
| | Inf9 | straight tail must be homozygous |
| "bicolored . . . . with a curly tail" | Inf10 | female, genotype $X^PX^G$ Ss and male, genotype $X^PY$ ss |
| and "purple . . . straight tail" | Inf11 | female gametes: $X^PS$, $X^Ps$, $X^GS$, and $X^Gs$. and male gametes: $X^Ps$ and Ys |

| GIVEN IN PROBLEM (P2) | | INFERENCE |
|---|---|---|
| "autosomal gene" | Inf1 | each sex has 2 alleles of the gene |
| "a second autosomal gene, assorting independently" | Inf2 | the 2 gene loci are on different autosomes (or widely separated on the same chromosome) |
| "3 alleles that show complete dominance" | Inf3 | 6 different genotypes possible representing 3 different phenotypes |
| "order of dominance is lanky is dominant to both medium and dwarf, and medium is dominant to dwarf" | Inf4 | lanky and medium may be homozygous or heterozygous |
| | Inf5 | dwarf must be homozygous |
| "2-toed being recessive to 4-toed condition" | Inf6 | 4-toed may be homozygous or heterozygous |
| | Inf7 | 2-toed must be homozygous |
| parental phenotypes | Inf8 | female, genotype Tt $Ll^D$ and male, genotype tt $l^dl^d$ |
| | Inf9 | female gametes: TL, $Tl^D$, tL, and $tl^D$. and male gametes: $tl^D$ |

**Figure 1: Selection of data given in the problems P1 and P2 and the inferences drawn that are relevant to the solutions of the problems.**

| Inference | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| XX/XY sex chromosome system | √ | √ | - | - | √ | - | - | - |
| male has one allele for X-linked gene and females will have 2 alleles | √ | √ | - | - | x | - | - | - |
| bicolor must be heterozygous | √ | √ | √ | √ | √ | √ | √ | √ |
| bicolor organism must be female | √ | √ | x | x | x | - | - | - |
| gene not on a sex chromosome | - | x | x | x | √ | √ | x | x |
| each sex has two alleles of the gene | - | x | √ | √ | √ | √ | √ | x |
| curly tail may be homozygous or heterozygous | - | x | √ | √ | x | √ | x | x |
| straight tail must be homozygous | - | √ | √ | √ | √ | √ | x | - |
| gene will assort independently of X-linked gene | - | - | √ | √ | - | - | x | √ |
| female genotype | x | x | √ | √ | x | √ | x | x |
| male genotype | x | x | x | x | x | x | x | x |
| appropriate female and male gametes | - | - | - | √ | - | x | x | - |
| Draw chromosomes | - | - | - | x | - | - | - | - |
| Use allele symbols | x | x | x | x | x | x | x | x |

√ correct x incorrect - no apparent attempt

**Figure 2: Analysis of performance of unsuccessful solvers on problem P1.**

| Inference | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| each sex has 2 alleles of the gene | √ | x | - | x | - | - | √ | √ |
| the 2 gene loci are on different autosomes (or widely separated on the same chromosome) | √ | x | - | x | x | - | √ | √ |
| six different genotypes possible representing 3 different phenotypes | x | x | - | x | x | - | - | x |
| lanky and medium may be homozygous or heterozygous | - | - | x | x | x | - | - | √ |
| dwarf must be homozygous | x | √ | - | √ | √ | - | √ | √ |
| 4-toed may be homozygous or heterozygous | - | x | - | - | - | - | x | √ |
| 2-toed must be homozygous | √ | √ | - | √ | √ | - | √ | √ |
| female genotype | √ | x | - | x | x | - | x | √ |
| male genotype | x | x | - | x | x | - | √ | √ |
| appropriate female and male gametes | √ | x | - | - | x | - | - | - |
| Draw chromosomes | x | x | - | - | - | - | - | - |
| Use allele symbols | x | x | x | x | x | x | x | x |

√ correct  X incorrect  - no apparent attempt

**Figure 3: Analysis of performance of unsuccessful solvers on problem P2**

| CRITICAL DECISIONS | OPTIONS |
|---|---|
| **Chromosomes** | |
| Number of pairs of autosomes | 1, 2 or 3 pairs? |
| Sex chromosome system | XX/XY, ZW/ZZ, or XX/XO? |
| Number of genes | 1 or 2? |
| **Decisions required for Gene 1 and Gene2** | |
| Number of alleles | 1, 2 or 3? |
| Relationship between alleles | Complete or partial dominance? |
| Function controlled by gene | Chosen from given list |
| Alleles and their symbols | Letter only to be chosen; with computer assigning appropriate symbol for each allele |
| Gene locus | Move arror over images of chromosomes to position required |
| Lethality | Include or exclude? |
| Mother's genotype | Selected from menu of genotype choices expressed using allele symbols above |
| Father's genotype | Selected from menu of genotype choices expressed using allele symbols above |

**Figure 4: Options available for critical decisions required to set up a genetic system with a microcomputer simulation, as used by students in attempting to solve problems C1 & C2.**

| | PROBLEM C1 | PROBLEM C2 |
|---|---|---|
| Chromosomal location of genes | 8/8 | 4/8 |
| Mother's genotype | 6/8 | 5/8 |
| Father's genotype | 6/6 | 7/8 |
| Answer i | 5/8 | 4/8 |
| Answer ii | 6/8 | 5/8 |
| Chromosomal diagram | 6/8 | 5/8 |

**Figure 5: Summary of success rate for steps in problems C1 and C2 in a computer based setting. Results are expressed as a fraction where 8 students attempted the problems.**